Solar Probe

Trajectory Analysis and Solar Gravitational Modeling

2003 NASA Academy Individual Project
NASA Goddard Space Flight Center
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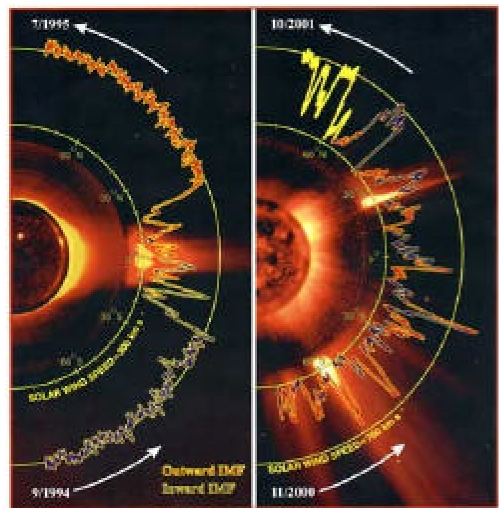
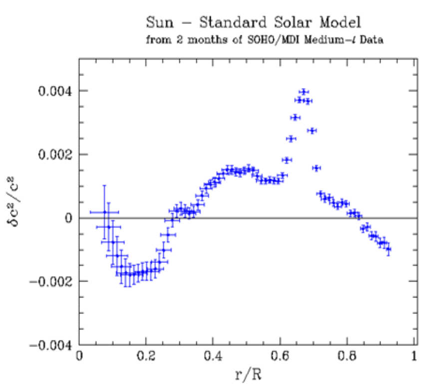
Background Information:

Solar Probe is an ambitious project that is designed to study several solar characteristics and processes:

- Solar Wind
  - Origins and Sources
  - Acceleration Processes
  - Space Weather
  - Changes with Solar Cycle
  - Coronal Heating
  - Corona Density Configuration



Data obtained from Ulysses at solar maximum (right) and solar minimum (left)



Sound speed variation with solar radius

- Verification of helioseismology probing of Sun's interior: Radial variation of mass density
- Time dilatation and general relativity: Orbit will precess 205 arcsec/century (compared with Mercury's orbit which precesses 43 arcsec/century).

In order to study these phenomenon **Solar Probe** is intended to make several passes very close to the sun (ultimately four solar radii from the sun's center). This presents many challenges:

- Spacecraft Protection
  - Verification of spacecraft thermal model near the Sun

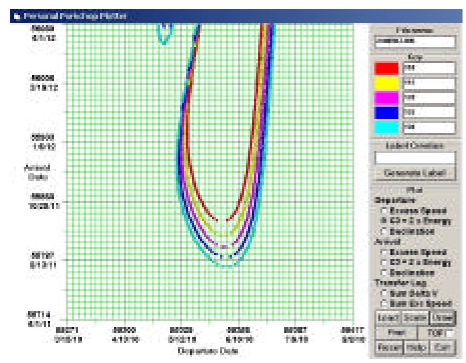
- Shielding delicate instruments from dust and radiation
- Amount of Scientific Data Attainable
    - Large orbital period
    - Small solar encounter time
- Communications
    - Angle Requirements between the spacecraft and the earth during the solar encounter (for Doppler shift effects)
    - Direct link to Earth to ensure data collection
    - X-Band and Ka-Band required

<u>Personal Contribution:</u>

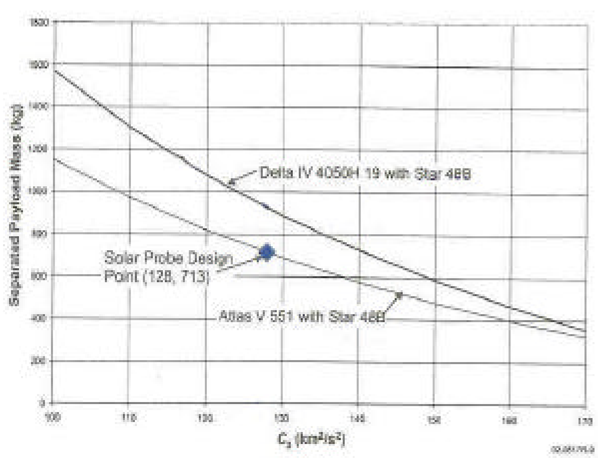
Verification of APL Trajectory

The Applied Physics Laboratory designed a similar Solar Probe Mission in 2002. As a starting point, the trajectory produced for the APL study was regenerated:

- Launch Dates
- Launch Energy
- Declination
- Launch Vehicle Selection
- General Trajectory



Plot of departure and arrival dates at Jupiter for various launch energy

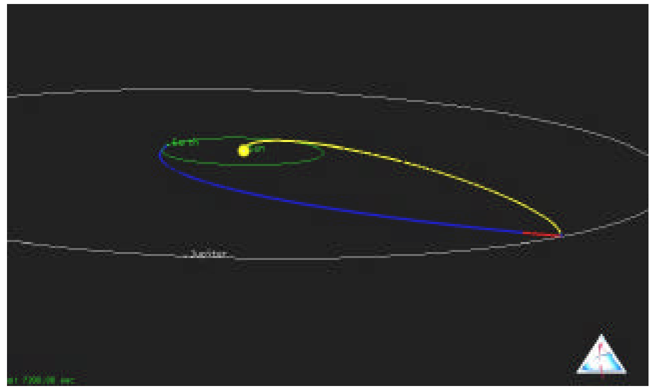


Plot of the payload mass for various launch energies for the Atlas V and Delta IV Heavy (both with Star 48B third stage)

The APL study used an Atlas V launch vehicle. Due to additional mass for maneuvers, a Delta IV Heavy is required for this mission.

Initial Orbit Analysis Goals:

- 5.66 perihelion radius
- 90 degree inclination
- Achieving correct alignment between the spacecraft and the Earth



Plot of the initial orbit conducted to achieve $5.66R_S$ perihelion and 90 degree inclination

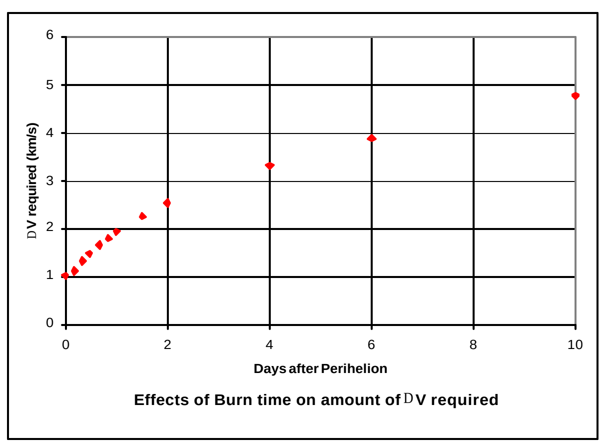
Modifications to Original Trajectory

Several changes were made to the APL trajectory to achieve the mission objectives:

- Initial perihelion radius of $5.66R_S$ rather than $4.0R_S$ in order to reduce the risk of inaccurate thermal models.
- Maneuver at prihelion to reduce the orbital period to one year (from four years) to increase the number of solar encounters and decrease the spacecraft lifetime.
- Maneuver at aphelion to move the perihelion radius to $4.0R_S$ is thermal models are verified.
- Instead of quadrature at perihelion, an angle of around 60 degrees between the spacecraft and the earth is desired. This allows for Doppler shift measurements that allow for the calculation of gravitational fields.

Maneuver Analysis

- Burn at (or close to) perihelion to achieve a period of one year
- Fuel Efficiency versus Spacecraft data collecting capabilities
- Burn at aphelion (if thermal models are accurate) to attain a perihelion radius of 4.0 solar radii



Plot of time after perihelion and velocity change required to achieve a period of 1 year

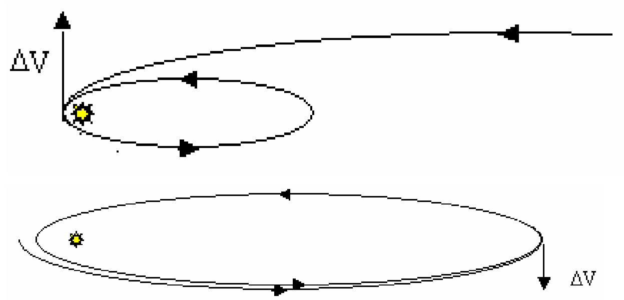
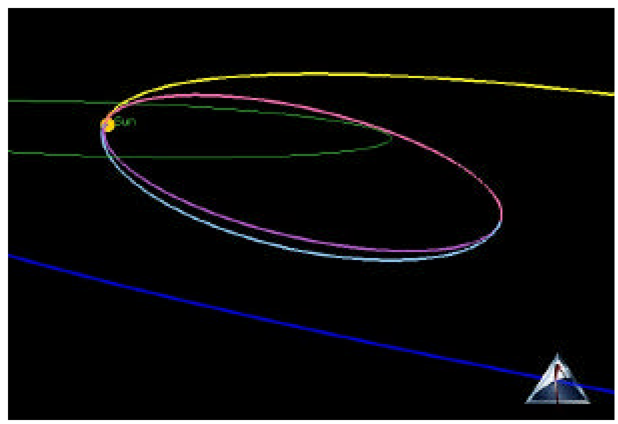


Diagram of each burn - The burn at perihelion (top) will reduce the period to 1 year. The burn at aphelion (bottom) will reduce the perihelion radius to 4.0 solar radii.

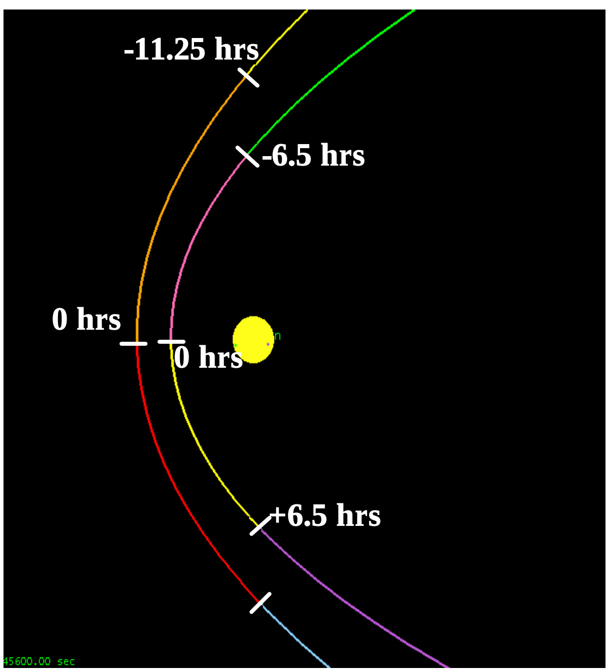
- Reducing period to one year
  - Burn location: perihelion
  - DV required: 1.0299 km / s
- Reducing R_p to 4.0 R_S
  - Burn Location: aphelion
  - DV required: 0.5430 km / s

Final Orbit Parameters

Period	0.944 year
Inclination	89.993 deg
R_a	1.976 AU
P_p	4.00 R_S
Angle between spacecraft and earth at perihelion	85.081 deg



Graphical representation of spacecraft trajectory around the sun



Close up of the Solar Encounter for a perihelion radius of 5.66 R_S (outer) and 4.0R_S (inner). Decreasing the perihelion radius cuts the solar encounter by almost 9 ½ hours.

Trajectory Timeline

- May 26, 2010: Launch into Earth Orbit (Delta IV)
- 24 minutes later: Leave Earth orbit, bound for Jupiter
- Sept. 3, 2011: Jupiter Swing By
- Jul 18, 2013: Arrival at Perihelion - Conduct first burn to reduce period to 1 year
- Jan 17, 2014: Conduct second burn at aphelion to reach R_p=4.0R_S
- Jul 17, 2014: Second perihelion pass at four solar radii

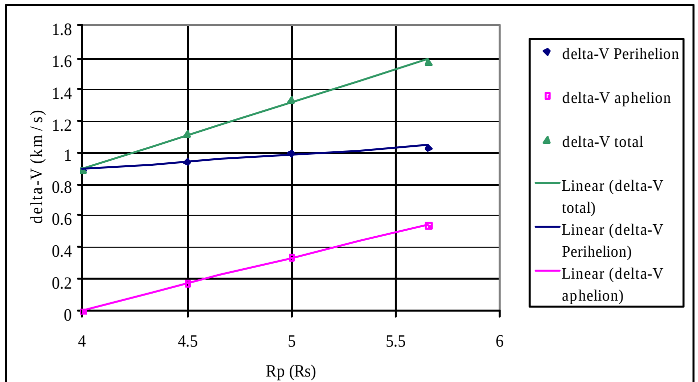
Fuel Requirements

- Burns (Isp=230 s): $M_{fuel}=M_{dry}(e^{\Delta V/(Isp*g)}-1)$=655.17 kgs
- Attitude Control: 6 kgs
- Margin (10 percent): 66.12 kgs
- **TOTAL: 727.29 kgs**

The mass allotted for fuel was 316 kg. This is significantly smaller than the amount of fuel required for the mission. Several options will be investigated to try to limit the propellant required or decrease the mass of the spacecraft.

Comparison of Initial Perihelion Radius to DV Requirement

Decreasing the initial perihelion radius will cause the velocity change to reach an orbit of one year to decrease. This is one method that could be used to decrease the propellant required; however, the margin for the thermal model would be compromised.



The Effects of Perihelion Radius on ΔV Requirements

As seen in the figure, the required velocity change is effected, but not by a very large amount.

Benefits Over Original Trajectory

- Shorter orbit period - Increases the number of solar encounters from 2 to 5 for the same mission duration.
- Reduced mission risk: Thermal loads at 5.66 RS are a factor 2 lower than the loads at 4.0 RS.

Conclusions and Future Work:

- An orbital period of one year with a perihelion radius of four solar radii was achieved, but a large amount of propellant is required.
- Investigate ways to minimize spacecraft or fuel mass
  - Minimizing mass of certain components
  - Using a bipropellant instead of a monopropellant
- Decrease the launch energy required, which would increase the mass available
- Examine methods to limit ΔV required
  - Decrease the initial perihelion radius
  - Increase the orbit period

- Placing the first maneuver such that there is a compromise between burn efficiency and scientific benefit
  - Conclusion: First maneuver must occur at perihelion because of fuel requirements
- Examine having an angle of 60 or 120 degrees between the spacecraft and the earth during solar encounters
  - Allow for measurements of doppler effects so that gravity calculations can be made.
- Modeling gravity field of the sun (as to not treat the sun as a point mass)
- See the effects of these models on the spacecraft's trajectory

References:

1. APL, *Solar Probe: An Engineering Study*; 2002

2. Satellite Tool Kit 4.3, Analytical Graphics, 2002

3. Brown, Charles D. , Spacecraft Mission Design Second Edition, American Institute of Aeronautics and Astronautics, Inc.; 1998

4. Sound speed Plot, http://soi.stanford.edu/results/sspeed.html

5. Solar max/min figure, http://spaceflightnow.com/news/n0110/16solarwind/ulysses.jpg

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